

Massive Stellar Clusters
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The Evolution of the Interstellar Medium Around Young Stellar Clusters

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Abstract. The interplay between the ISM and the massive stars formed in clusters and, more generally, in recent events of star formation is reviewed via the global effects each has on the other. The pre-existing environment affects the properties of the massive stars, the duration of the star-forming event and could potentially affect the IMF. The collective effect of massive-star winds and supernova explosions creates a structured ISM by forming bubbles, supershells and, in more extreme cases, by inducing large-scale gas outflows. Gas/dust removal may quench star formation in young stellar clusters. Conversely, supernova-driven shocks may trigger star formation in molecular clouds surrounding the stellar clusters. Metal ejection from the massive stars is responsible for the pollution of the ISM and, if the metal-rich gas can escape the galaxy's gravitational potential, of the IGM. The environment where stellar clusters form is populated by a diffuse stellar population which contributes between 50% and 80% of the total UV light. The investigation of the nature of the diffuse UV light is the subject of a study employing HST STIS spectroscopy, whose preliminary results are presented and briefly discussed.

1. Introduction

Stellar clusters are a prominent product of events of star formation. The study of young stellar clusters has recently received new impetus after the suggestion

that the most massive among such systems may be progenitors of globular clusters (Kennicutt & Chu 1988, Lutz 1991, Holtzmann et al. 1992, Whitmore et al. 1993, O’Connell, Gallagher & Hunter 1994, Meurer et al. 1995, Ho & Filippenko 1996, to quote a few). In this review, we discuss the relation between young stellar clusters and the surrounding environment, both gaseous and stellar. The interplay between massive stars and ISM, for instance, plays a crucial role in the evolution of a burst of star formation. Young stellar clusters are thus discussed here in the context of spatially extended, active star-formation events (starbursts). Because of the vastness of the topic, this review is necessarily incomplete, and many significant contributions may have been, unwillingly, overlooked.

2. The Effects of the Environment on the Stellar Clusters

The environment affects or can affect to various degrees characteristics of the stellar clusters/star-forming regions. Three such effects are briefly discussed below.

- The metallicity of the cloud from which the stars form correlates with the massive stars’ wind properties and with the number of Wolf-Rayet stars produced. Both effects contribute to increase the mass loss from the stars and the momentum and energy transfer into the surrounding medium for increasing metallicity (Leitherer 1993). If the metallicity is above solar, stellar winds are more important than supernovae for the energy deposition rates in star formation episodes younger than ~ 20 Myr. From an observational point of view, the dependence of the evolutionary history of the OB population on metallicity should result in a correlation between the wind lines produced by O-stars, such as SiIV($\lambda 1400$ Å) and CIV($\lambda 1550$ Å), and the metallicity of the region. A correlation between the strength of the combined equivalent widths of SiIV and CIV and the oxygen abundance has been indeed observed in starburst galaxies, as shown in Figure 1 (from Heckman et al. 1998, see also Storch-Bergmann, Calzetti & Kinney 1994).

- The gas supply determines the maximum duration of a star-forming event. This effect is not generally observable in individual stellar clusters, which can be considered single-age populations (with spreads ≤ 10 Myr, e.g. Massey, Johnson & DeGioia-Eastwood 1995a). It is observable within star-forming regions taken as a whole, like Giant HII regions (e.g., 30 Doradus) or starbursts (e.g., NGC5253), where multiple stellar clusters and OB associations spanning a range of ages are usually present (e.g. Calzetti et al. 1997, Grebel & Chu 2000). In rigorous terms, the gas supply is not the only parameter to be considered for the starburst duration, as more complex interactions between massive stars and their surrounding environment take place (see next section).

- The relation between environment and stellar Initial Mass Function (IMF) is probably the most controversial topic. A complete review of the current status of IMF studies is contained in the Proceedings of the 38th Herstmonceux Conference (Gilmore & Howell 1998). The underlying reason for the ongoing controversy is that no unique theory for the observed mass spectra exists yet (e.g. Clarke 1998), and observations are still not entirely effective at constraining theories. If we parametrize the IMF as $\phi(m) \propto m^{-\alpha}$, the slope in stellar clusters

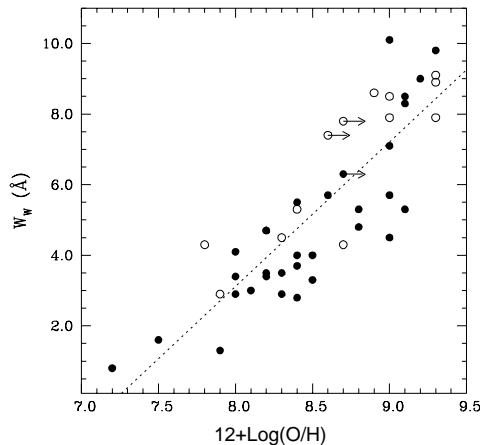


Figure 1. The sum of the SiIV($\lambda 1400 \text{ \AA}$) and CIV($\lambda 1550 \text{ \AA}$) equivalent widths, W_W , as a function of the oxygen abundance for a sample of starburst galaxies, from Heckman et al. (1998). The two lines have been measured from IUE spectra of the galaxies, and trace primarily the hot-star winds in systems with active star formation, although a significant contribution from interstellar absorption lines may also be present. The poor spectral resolution of IUE does not permit, in fact, the discrimination between wind lines and interstellar lines.

is $\alpha \approx 2.3\text{--}2.5$ for masses above $M \approx 1 M_\odot$ (see summary review by Kroupa, these Proceedings). The observed slope is for all practical purposes a ‘Salpeter slope’. There appear to be no systematic variations in the IMF slope between the Milky Way, the LMC and the SMC stellar clusters, for masses above $5\text{--}10 M_\odot$ (Massey et al. 1995a,b), nor a measurable variation in upper mass cut-off, which is $>70\text{--}100 M_\odot$; this lack of a systematic trend covers about a factor 10 in metallicity and a factor ~ 1000 in stellar density (Massey 1998). However, the scatter around the mean slope is $\Delta\alpha \sim 0.5$, which is variously interpreted as an effect of observational uncertainties, environment-dependent variations (Scalo 1998), or stochastic scatter from a universal slope (Elmegreen 1999). Below $M \approx 1 M_\odot$, the IMF can be described either as a log-normal distribution (Paresce & De Marchi 1999) or by two power-laws, with much flatter slopes than Salpeter, $\alpha \approx 1.5$ for $M < 0.5 M_\odot$ and $\alpha \sim 2.2$ for $0.5 M_\odot < M < 1 M_\odot$ (e.g., Kroupa, Tout & Gilmore 1993), in both cases with a smaller scatter than in the higher mass region.

3. The Effects of the Stellar Clusters on the Environment.

The impact of stellar clusters on the surrounding ISM is mediated by the effects of hot-star winds and supernova explosions in terms of mass and metal deposition, and energy and momentum transfer.

- In an evolving burst of star formation, the energy injected into the ISM by the collective effect of massive-star winds and SNa explosions may sweep up material and produce structures in the form of bubbles, supershells, and filaments (Shull 1993, Chu & Kennicutt 1994). In more extreme cases, large-

scale outflows of material, or superwinds, may be produced (Heckman, Armus & Miley 1990). 30 Doradus in the LMC, which has been called the ‘Rosetta Stone of Starbursts’ (Walborn 1991), is the prototype of turbulent environment; here the filamentary interfaces between ‘evacuated’ regions and surrounding dust clouds dominate the nebular emission (Scowen et al. 1998, Walborn et al. 1999). The gas kinematics reveal the complex structure of the 30 Dor region: slow expanding shells ($v < 100 \text{ km s}^{-1}$ and sizes up to $\sim 100 \text{ pc}$), driven by stellar winds and SNe, are present together with fast expanding shells ($v \sim 100\text{--}300 \text{ km s}^{-1}$ and sizes up to $\sim 30 \text{ pc}$), these most likely driven by SNRs (Chu & Kennicutt 1994). The massive-stars- and SNe-induced gas removal from the stellar cluster’s site will have the effect of quenching star formation in that region, thus producing a large-scale self-regulating mechanism for the star formation intensity (e.g., Kennicutt 1989, Heckman 1997).

- The energy and momentum injection by evolving and exploding massive stars can also cause destruction/removal of dust from the site of star formation. While gas outflows can eject significant amounts of both interstellar gas and dust from the star-forming region, shocks from SNe can be responsible for the dust grain destruction, via grain-grain collisions and sputtering (Jones et al. 1994). As a net result, the main source of opacity for the starburst and the stellar clusters is the dust *surrounding* the region of star formation, rather than the dust inside the region. The dust geometry will then be equivalent to a shell surrounding a central light source (Calzetti, Kinney & Storchi-Bergmann 1996).

- Hot-star winds and SNa explosions can drive ionization and shock-fronts through molecular clouds, causing star formation to propagate (Elmegreen & Lada 1977). Although controversy exists on the theory of star formation propagation (McCray & Kafatos 1987), triggered star formation has been advocated for the multiple generations of stellar clusters observed in 30 Doradus (Hyland et al. 1992, Walborn et al. 1999, see also Grebel & Chu 2000) and in starburst galaxies like M82 and M83 (Satyapal et al. 1997, Puxley, Doyon, & Ward 1997), where time scales for star formation have been measured to span a few tens of Myr.

- The material ejected by supernovae pollutes the ISM with about $1 M_{\odot}$ of metals for every $\sim 40 M_{\odot}$ of new stars formed, assuming a Salpeter IMF. Effects of localized metal pollution due to the presence of young stellar clusters have been observed by Kobulnicky et al. (1997) in the nearby starburst dwarf NGC5253, where an enhancement of Nitrogen over Oxygen by a factor 3 has been measured in regions in the immediate proximity of a stellar cluster. If gas outflows from the region of star formation develop into large-scale superwinds, these can carry metals out of the galaxy and contribute to the enrichment of the IGM. This mechanism will be more efficient in low-mass galaxies, where the escape velocity is smaller than in more massive galaxies. A starburst with a mechanical luminosity of $10^{38} \text{ erg s}^{-1}$, hosted in a $10^9 M_{\odot}$ galaxy, will produce enough energy to eject about 70% of the newly formed metals into the IGM (MacLow & Ferrara 1999); this fraction obviously increases for more luminous starbursts and for decreasing galaxy mass.

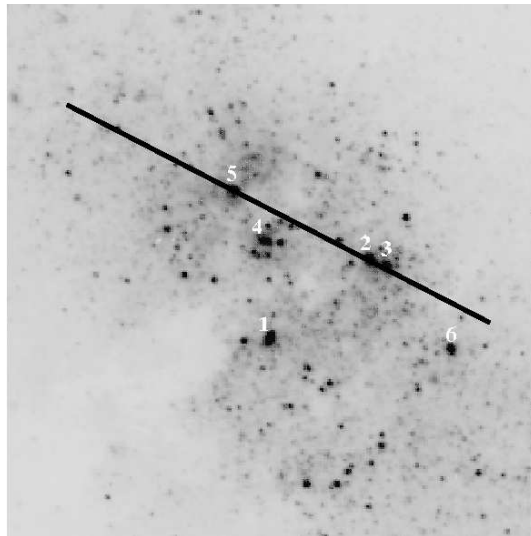


Figure 2. HST WFPC2 image of the central ~ 500 pc of NGC5253, in the F547M filter ($\sim V$). North is up, East is left. The numbers label the six brightest stellar clusters, whose general properties are discussed in Calzetti et al. (1997). The lighter region crossing the center of the image from SE to NW locates the position of the dust lane. The black line marks the approximate position of the STIS $0.1''$ slit used to obtain UV spectra of clusters 2, 3, and 5, and of the field surrounding the clusters, with an approximate spectral resolution of $\sim 2 \text{ \AA}$.

4. A Case Study: Stellar Clusters in NGC5253

In starburst regions, young stellar clusters are generally embedded within diffuse UV light, which represents about 50%, and up to 80%, of the UV brightness of the region (Conti & Vacca 1994, Hunter et al. 1994, O’Connell et al. 1994, Meurer et al. 1995). The nature of the diffuse UV light is still unclear; scattered light from the stellar clusters, small unresolved stellar clusters, a diffuse stellar population originating as an independent mode of star formation, or stars left behind by dissolved clusters are all possible interpretations.

Long-slit ultraviolet spectra of the central starburst in the nearby ($D \sim 4$ Mpc) dwarf galaxy NGC5253, obtained with STIS on-board HST, are being employed to investigate the nature of the diffuse UV light (Tremonti et al. 2000). NGC5253 is a “benchmark starburst”, with active star formation concentrated in the central $\sim 20''$ (about 400 pc at the distance of the galaxy), superimposed on an older, quiescent stellar population. The central star-forming region is very blue, although it is crossed by dust lanes which produce patchy and heavy obscuration. The starburst region contains about a dozen bright stellar clusters (Meurer et al. 1995), the six brightest of which are identified in Figure 2 (from Calzetti et al. 1997). Clusters 4 and 5 are located within the most active part of the starburst, which is ~ 100 pc in size and has a star formation rate density of $\sim 10^{-4} M_{\odot} \text{ yr}^{-1} \text{ pc}^{-2}$, corresponding to the maximum levels observed in starburst galaxies (Meurer et al. 1997). The $H\alpha$ emission from the galaxy has

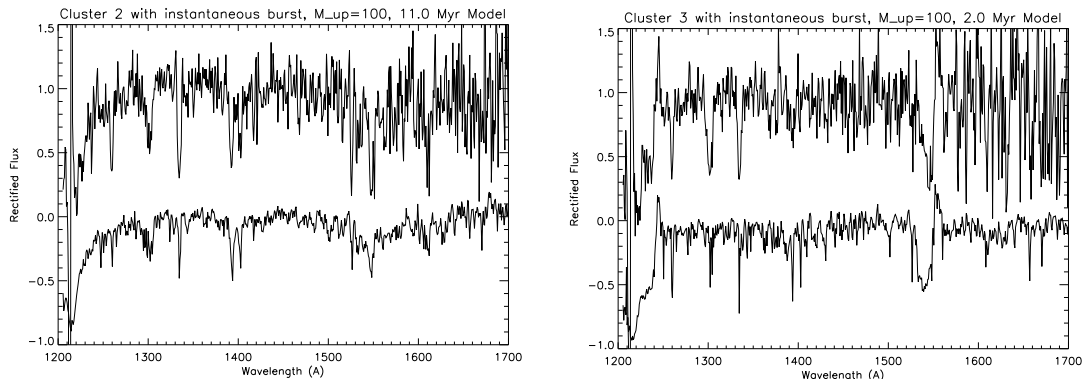


Figure 3. Rectified UV spectra of clusters 2 (left) and 3 (right). In each panel, the data (top) and the preliminary best fit stellar population models (bottom) are shifted relative to each other. The best fit instantaneous-burst stellar populations have ages 11 Myr and 2 Myr for cluster 2 and 3, respectively, using a Salpeter IMF with an upper mass cut-off of $100 M_{\odot}$.

almost perfect circular symmetry around cluster 5, which is thus driving the ionization. This cluster is deeply buried in the dust lane crossing the center of the galaxy, with an optical depth $A_V \approx 30$ mag (Calzetti et al. 1997).

Previous HST WFPC2 broad- and narrow-band imaging of the center of NGC5253 at both optical and ultraviolet wavelengths had yielded tentative ages for the six stellar clusters of Figure 2. In particular, the colors and the $H\alpha$ emission of cluster 5 suggested this cluster to be the youngest among the six, with an age < 3 Myr; clusters 2 and 3 came out to be the oldest, with ages estimated between 30 and 60 Myr (Calzetti et al. 1997). These three clusters, together with the field between them, are the targets of our STIS UV spectroscopic observations, as shown in Figure 2.

The rectified UV spectra, in the wavelength range 1,200–1,700 Å, of clusters 2, 3, and 5, and of the field between them are shown in Figures 3 and 4. Preliminary fits to the spectra using the stellar population synthesis models of Leitherer et al. (1999, recently updated to include B stars), are shown in the same figures, down-shifted relative to the observational data. Instantaneous burst populations have been adopted for all the spectra, although, for the field, the case of continuous star formation is currently being investigated. The metallicity used in the fits is $0.2 Z_{\odot}$, a good match to the metallicity of the gas in the galaxy, which is about $1/6$ solar. A range of IMF slopes and upper mass cut-offs are also being tested on the data; the preliminary results reported here use a Salpeter slope and upper mass cut-off of $100 M_{\odot}$.

The best fit ages of clusters 2 and 3 are 11 Myr and 2 Myr, respectively, a factor 5 and 20 younger than the ages inferred from the HST broad-band colors. For instance, the presence of P-Cygni profiles in the lines of NV($\lambda 1240$ Å) and CIV($\lambda 1550$ Å) exclude ages older than ~ 6 Myr for cluster 3. Cluster 5 is confirmed to be very young: the best fit model to the UV spectrum gives an age ~ 1 Myr. The very red spectral continuum also confirms that the cluster is

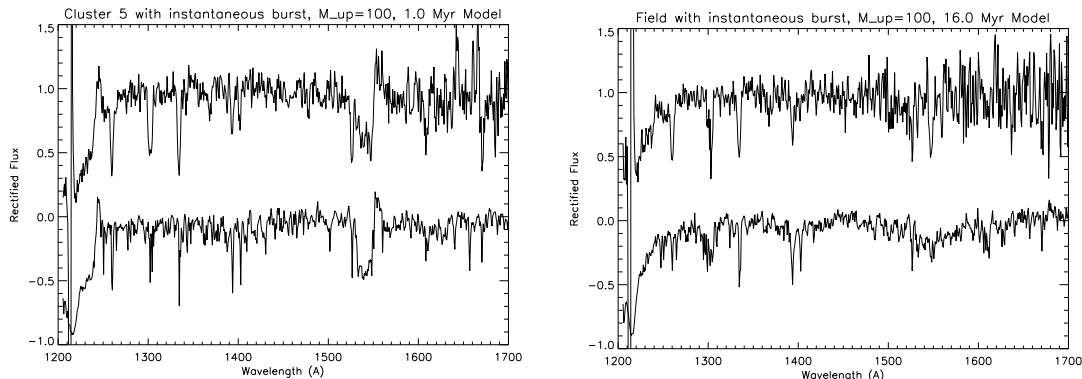


Figure 4. As in Figure 3, for cluster 5 and for the field surrounding the three clusters. The best fit instantaneous-burst stellar population gives an age ~ 1 Myr for cluster 5 and 16 Myr for the field.

reddened by a considerable amount of dust; depending on the dust obscuration correction, the inferred mass for cluster 5 is between a few times 10^5 and $10^6 M_{\odot}$; this cluster is thus a ‘bona fide’ super-star-cluster candidate (Calzetti et al. 1997).

The first remarkable property of the field’s UV spectrum is that the lines corresponding to NV, SiIV and CIV are different, both qualitatively and quantitatively, from the stellar lines in the clusters’ spectra. This excludes the possibility that the field UV light is dominated by scattered cluster light. This is further supported by the fact that the HST WFPC2 UV image shows resolved small clusters and bright isolated stars in the region we call the ‘field’. A preliminary best fit model using an instantaneous burst population with Salpeter IMF gives an age of 16 Myr. The stellar population in the field, thus, appears older than the populations in the bright stellar clusters. Cluster 4 has, indeed, an age ~ 4 Myr, and clusters 1 and 6 have ages < 15 – 17 Myr (Calzetti et al. 1997). The old age of the field may indicate that its stellar population originates from unresolved stellar clusters older than the 6 brightest ones, or from stars left behind by dissolved clusters. An alternative interpretation is that the IMF of the field is drastically different from the IMF of the stellar clusters (e.g., Massey et al. 1995b). All three possibilities are currently under investigation.

5. Summary

The investigation of the interplay between recently formed stellar clusters and the surrounding ISM is the key to understand the evolution of star-forming events. For instance, the duration of a burst of star formation is determined not only by the gas supply, but also by the feedback of the massive-star winds and SNa explosions into the ISM, which may quench or possibly trigger new star formation. In this review, we have highlighted, among other things, the impact of the pre-existing environment on the properties of the newly formed massive stars and presented some of the ongoing controversy on environment-dependent IMFs. The feedback of stellar clusters onto the surrounding ISM can

be summarized as the collective mass, metals, energy and momentum deposition by massive stars; the general effects will be the creation of a highly structured environment and the metal pollution of both ISM and IGM.

Diffuse UV-bright stars are generally found in the same environment where young stellar clusters are located. Understanding the nature of the diffuse population is key to understanding star formation mechanisms; competing theories include unresolved stellar clusters, dissolved stellar clusters, and a second mechanism for star formation. We have briefly presented the ongoing analysis of recently obtained HST STIS UV spectra of stellar clusters and diffuse population in the nearby starburst galaxy NGC5253; the goal of the analysis is to constrain the above scenarios.

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Q. (Daniel Schaerer): From optical spectroscopy we know that your knots # 4 and 5 in NGC5253 have some WR stars, which have allowed us to determine ages of $\sim 2\text{--}5$ Myr. Could you please comment on the difference with the very young age you determine for cluster # 5? Also, it would be interesting to get an optical spectrum of cluster # 3, for which you find an age young enough to expect WR stars. Do you have such data?

A.: The age we derive for cluster # 4 from HST broad-band colors and H α emission is $\sim 2.5\text{--}4.4$ Myr, compatible with the presence of WR stars. The

position of your slit misses the center of cluster # 5, so our age determination for this cluster is not necessarily incompatible with your detected WR stars. Cluster # 5 ‘sits’ on a region of very active star formation, and I believe not unlikely that multiple generations of stars are contemporary present in that region. We don’t have an optical spectrum of cluster # 3; it would be interesting to get one, in order to address your last question.